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A comparative study of dc biased RF impedance probes and Langmuir probes for the measurement of processing plasma parameters

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Abstract
In this work, we compare measurements of electron density (n_e), plasma potential (φ_p), electron temperature (T_e), and electron energy distribution function (EEDF or $f(E)$) made with a dc biased RF probe and a Langmuir probe. The measurements show good agreement between the two probes across an order of magnitude in plasma density.

(Some figures may appear in colour only in the online journal)

1. Introduction

Researchers desiring measurements of plasma density (n_e), plasma potential (φ_p), electron temperature (T_e) and electron energy distribution function (EEDF or $f(E)$) with a single instrument, have typically had only one recourse, the Langmuir probe. However, in recent years, research [1–3] has demonstrated the RF probe's ability to measure the EEDF, and plasma potential, along with electron density. What has been missing is a direct comparison between Langmuir probes and RF probes in the context of measuring the full range of plasma parameters described above (φ_p, T_e, EEDF, and n_e). This work fills that need.

Langmuir probes measure the sum of the dc electron and ion currents, with the electron current dominating when $V_{dc} \geqslant \phi_p$ (where V_{dc} is the dc bias on the probe) and the ion current dominating when V_{dc} is well below ϕ_p. In principle, data from either regime can be used to determine n_e, but in practice the values can differ substantially and depend greatly on assumptions regarding the manner in which ions are collected by the probe [4]. In addition, values for T_e are needed for both the ion and electron saturation cases, so neither of these techniques offers a direct measurement of n_e. Alternatively, the electron density can be obtained by first determining ϕ_p and then f(E). Determining either parameter takes two derivatives with Langmuir probes where each derivative amplifies the effective noise level. Ideally the ion current I_i should be subtracted from the total dc current I_t. However, because I_i is neither known nor measured, it is often simply neglected, based on the assumption that I_i varies far more slowly with V_{dc}, than does the electron current I_e. Unfortunately, the noise associated with I_i is not small, and this noise can easily swamp derivatives in I_e when V_{dc} is large and negative [5]. Obtaining smooth and clean values for f(E) at high energy is therefore difficult with Langmuir probes, unless the plasma is extremely stable and quiescent and the results are averaged over long times. Also, since Langmuir probes utilize dc current collection to examine the plasma, they are strongly influenced by plasma drift, energetic particle beams and potentially secondary electron emission. In principle, RF probes offer solutions to a number of the issues mentioned above.

RF probes operate on the principles of antenna impedance in a plasma and resonance effects observed at the plasma frequency, an area that incorporates an extensive body of research going to back to the late 1950s [6–9]. RF probes are of particular interest for applications where plasma density is difficult or impossible to measure using a Langmuir probe. They have seen use in a number of plasma physics applications across a wide range of disciplines including space

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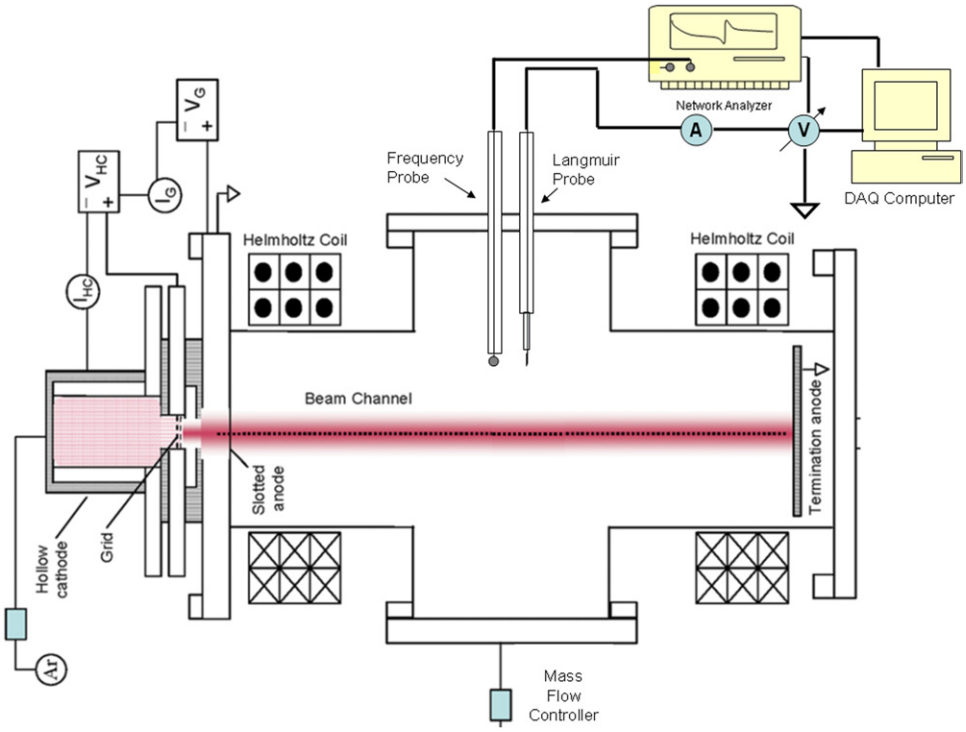

Figure 1. Diagram of the electron beam plasma processing chamber showing the plasma diagnostic configuration.

physics research [10], ion thruster measurements [11] and in reactive gas and depositing processing plasmas [12]. For density measurements RF probes are particularly well suited, since high-frequency RF signals can easily pass through thin insulating layers and thus are not significantly affected by the deposition of thin films. RF probes can measure n_e accurately and unequivocally in a wide range of gases and plasmas, including those used for etching or surface deposition. In addition, the determination of n_e (from plasma resonances) is direct, unlike with Langmuir probes where n_e is calculated.

While the initial interest in frequency probes grew out of a need for density measurements in harsh plasma environments, this work focuses on a much broader range of plasma parameters obtained by combining RF plasma impedance measurements with a variable dc bias. This technique, which was outlined recently by Walker *et al* [13], extends the RF probe's abilities by measuring both the real and imaginary parts of the complex impedance Z_{ac} as a function of V_{dc} over a wide range of frequencies, and provides a determination of φ_p, T_e, EEDF and n_e. This is similar to Langmuir probe methods, but has fewer complications. Specifically, the RF technique requires only one derivative to obtain $f(E)$ whereas two derivatives are required with Langmuir probes. Noise amplification from differentiating the raw data is thus lessened. In addition, RF probes can virtually eliminate the ion component of the ac current by operating above the ion plasma frequency ω_{pi}. In principle, this allows for more reliable data collection at highly negative bias voltages, where the dc ion current exceeds the electron current. Also, while Langmuir probes are strongly influenced by plasma drift, energetic particle beams and potentially secondary electron emission, these processes have little effect on RF probes at high frequency, other than to modify the sheath around the probe. The effects are weak because RF probes measure ac current only.

In this work, we focus on using the Walker technique to measure electron temperature, EEDF, and φ_p. Electron density, n_e, is then determined by integrating the EEDF, and those results are then compared with the values inferred from high-frequency measurements used to determine the electron plasma frequency [14, 15]. The RF probe values are also compared with nearby Langmuir probe measurements. The plasma characterized in this study is a steady-state argon plasma generated by a 1 kV electron beam in the Plasma Applications Laboratory at the Naval Research Laboratory. Care was taken to avoid making the probe measurements within the electron beam volume, in order to avoid the complications seen with Langmuir probes discussed above. The results indicate that RF probes are as effective, and in some cases have advantages over Langmuir probes in measuring the standard plasma parameters $f(E)$, T_e, φ_p and n_e.

2. Experimental setup and procedure

2.1. Processing chamber and electron beam source

The measurements detailed in this work were performed in a stainless-steel vacuum vessel enclosed by magnetic field coils that produce a uniform axial magnetic field within the chamber. The vacuum chamber houses a hollow-cathode electron beam source, a termination anode for the electron beam and a Langmuir probe and an RF probe mounted on linear motion feedthroughs. A diagram of the experimental setup is shown in figure 1.

The electron beam source consists of a rectangular hollow-cathode discharge held a few hundred volts negative with respect to a semi-transparent anode mesh. The anode mesh is constructed of a grid of stainless-steel wires woven to produce 75 μm × 75 μm openings with 34% total transparency, and provides a barrier between the hollow cathode discharge plasma and the beam generated plasma downstream from the mesh. The anode mesh is biased negatively with respect to a slotted grounded anode so that electrons extracted from the hollow cathode discharge are accelerated to high energy. Importantly, this configuration allows the beam current to be varied independent of the background pressure and the acceleration voltage, because the hollow-cathode voltage independently controls the beam current.

The rectangular geometry produces an electron beam in the form of a thin sheet that extends to a grounded termination anode at the opposite end of the vacuum vessel, with the axial magnetic field preserving the beam geometry and producing a similarly shaped plasma. Further details can be found in [16]. For the results reported here the acceleration voltage was ∼1 kV.

2.2. RF impedance probe and calibration

The RF probe used for these experiments consisted of a small stainless-steel sphere of radius 0.5 mm attached to one end of a piece of rigid coaxial cable. Due to the small size of the probe relative to both the wavelengths of the applied ac signal, and the gyro-radius of electrons, the surface fields are treated electrostatically. The other end of the coaxial cable was connected to an HP 8753D Network Analyzer through 50 Ω, RG 303 coaxial cable. The supply used to apply dc bias to the probe was an SRS Keithly 2400 variable voltage supply. LabVIEW™ was used to control and manage data acquisition from both the network analyzer and the variable voltage supply.

When the probe is connected to the network analyzer, the complex reflection coefficient, Γ, is measured over a range of frequencies and the impedance of the system calculated according to

$$Z(\omega) = Z_0 \frac{1 + \Gamma(\omega)}{1 - \Gamma(\omega)}, \tag{1}$$

where Z_0 is the analyzer internal impedance of 50 Ω. This measurement technique requires the user to properly calibrate the probe in order to eliminate stray capacitances and inductances from the cabling and other components. This is done by building calibration loads consisting of a matched 50 Ω load, an electrical short and open termination which are calibrated to provide Γ values of 0, −1 and 1, respectively. Once this calibration is completed, the impedance characteristics of the plasma surrounding the probe can be measured. For a more detailed description of this procedure see [15].

2.3. Measuring φ_p and EEDF with a dc biased RF impedance probe

The summary detailed below is intended to elucidate the experimental technique employed in this work, but leaves out many of the finer points of RF impedance probe theory. For the interested reader, a more complete discussion of the theoretical basis of low-frequency RF probe measurements is provided in [13].

Measuring φ_p and then the EEDF involves applying a variable dc bias to the RF probe. The network analyzer provides an additional small ac signal that provides a means to measure the ac impedance of the plasma as a function of dc bias. When an RF probe is immersed in plasma and the applied frequency satisfies $f \ll \omega_{pe}/2\pi$, the ac impedance is primarily resistive. Here ω_{pe} is the electron plasma frequency. The addition of the small RF field slightly modifies the current collection of the probe at each dc bias setting, and the real part of the impedance, measured by the network analyzer, can be written as

$$Re(Z_{ac}) = \frac{R_{ac}}{1 + (\omega R_{ac} C_{ac})^2}, \tag{2}$$

where R_{ac} is the ac resistance and C_{ac} is the ac capacitance [13]. Furthermore, if the probe is constructed properly to ensure low capacitance, and if the frequency regime is carefully chosen, the network analyzer provides a direct measure of the plasma's ac resistance. That is, if the probe is designed so that

$$\omega R_{ac} C_{ac} \ll 1, \tag{3a}$$

then

$$Re(Z_{ac}) \cong R_{ac} \tag{3b}$$

over a wide range of dc bias.

Since the ac voltage V_{ac} (a few mV) from the network analyzer is much less than the dc bias V_{dc} (a few volts), the magnitude of the ac component of the collected current is essentially equal to $V_{ac}(dI_e/dV_{dc})$, where I_e is the dc electron current collected by the probe. Thus,

$$R_{ac} \cong \left(\frac{dI_e}{dV_{dc}}\right)^{-1}. \tag{4}$$

In essence the network analyzer gives the slope of the I_e–V_{dc} characteristics of the probe immersed in the plasma, thereby providing the user with a direct measure of the first derivative of the dc electron current. A related technique was introduced by Boyd and Twiddy [17] using lower frequencies that do not allow separation of ion and electron effects.

As probe bias is varied, the plasma potential, φ_p, is indicated by a minimum in R_{ac}. If the probe is properly constructed so as to remove capacitive contributions to the impedance as prescribed in equation (3*a*), the plasma potential occurs at the bias where

$$\frac{dRe(Z)}{dV_{dc}} = 0. \tag{5}$$

Given φ_p, the EEDF can be found using the formalism given by Druyvesteyn [18] in which e is the electronic charge, A is the probe surface area, m_e is the electron mass and I_e is the electron current collected by the probe:

$$f(E) = \frac{4}{e^3 A}\sqrt{\frac{m_e E}{2}}\left(\frac{d^2 I_e}{dV_{dc}^2}\right)\Bigg|_{V_{dc}=\varphi_p - E/e}. \tag{6}$$

This expression can be recast in terms of R_{ac} and then in terms of Re (Z_{ac}), provided that condition (3*a*) is met, as follows:

$$f(E) = \frac{4}{e^3 A}\sqrt{\frac{m_e E}{2}}\left(\frac{\mathrm{d}R_{ac}^{-1}}{\mathrm{d}V_{dc}}\right) \cong \frac{4}{e^3 A}\sqrt{\frac{m_e E}{2}}\left(\frac{\mathrm{d}\,Re(Z_{ac})^{-1}}{\mathrm{d}V_{dc}}\right)\Bigg|_{V_{dc}=\varphi_p - E/e}. \quad (7)$$

Equation (7) provides a straightforward method for calculating the EEDF of a plasma based on the Z_{ac} measurements recorded by a network analyzer operating at low frequency. This method has two advantages over the analogous technique for calculating the EEDF with Langmuir probes:

(1) Only one differentiation is required to obtain $f(E)$ as described in equation (7). This reduces the detrimental effect of signal noise.
(2) Langmuir probes measure both electron current, I_e, and ion current, I_i, as part of the total collected current. As noted earlier, the ion current is not of great concern near φ_p because I_e varies much more rapidly than I_i. However, at large negative biases $I_i \gg I_e$. To treat this regime, an assumed form for $I_i(V_{dc})$ is commonly used. By contrast, this complication can be eliminated with RF probes by choosing frequencies such that $\omega > \omega_{pi}$. Only electron current then influences Re(Z_{ac}) significantly since the ac frequency changes too rapidly for ions to respond. ac frequencies between 5 MHz and 20 MHz were used for this work, depending on the plasma density.

2.4. Measuring φ_p and EEDF with a Langmuir probe

The Langmuir probe used in these measurements was constructed from ceramic and stainless-steel tubes. The tip was a loop of tungsten wire with an exposed area of 3×10^{-6} m^2. The I–V characteristics of the probe were obtained using a Stanford Research SR245, Keithley 2400 variable voltage supply. LabVIEW™ was used to control the bias supply and manage data acquisition. EEDFs obtained using the Langmuir probe were measured using the Druyvesteyn formula from equation (6), but without correcting for the ion current. The plasma potential was found by determining the bias voltage where $\mathrm{d}^2 I/\mathrm{d}V_{dc}^2 = 0$. To obtain the electron density (n_e), $f(E)$ was integrated numerically:

$$n_e = \int_0^\infty f(E)\,\mathrm{d}E. \quad (8)$$

3. Experimental results and discussion

This section presents a comparison of several plasma parameters acquired using the methods described in section 2. The results below were acquired in an argon electron beam-generated plasma, with the axial magnetic field constrained so that the electron cyclotron frequency $\omega_{ce} \ll \omega_{pe}$. This condition, combined with the small size of the probe, ensures that magnetic effects are weak. All measurements reported in this section were performed ~2 cm outside the beam volume so as to minimize complications from beam interactions with the probe.

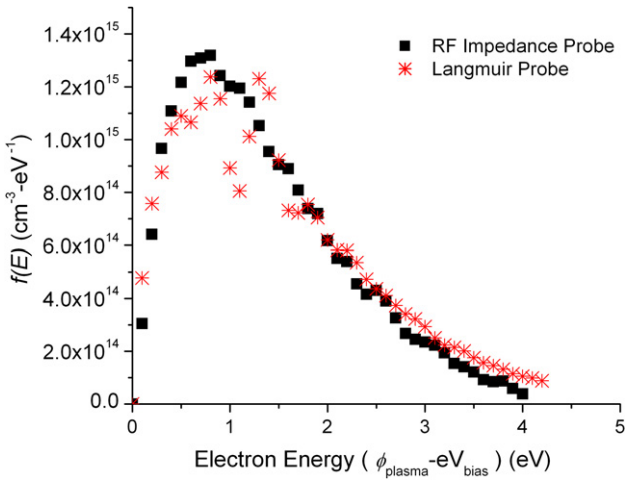

Figure 2. A comparison $f(E)$ measured by an RF probe and Langmuir probe. Five point moving averages of the raw data are shown as well.

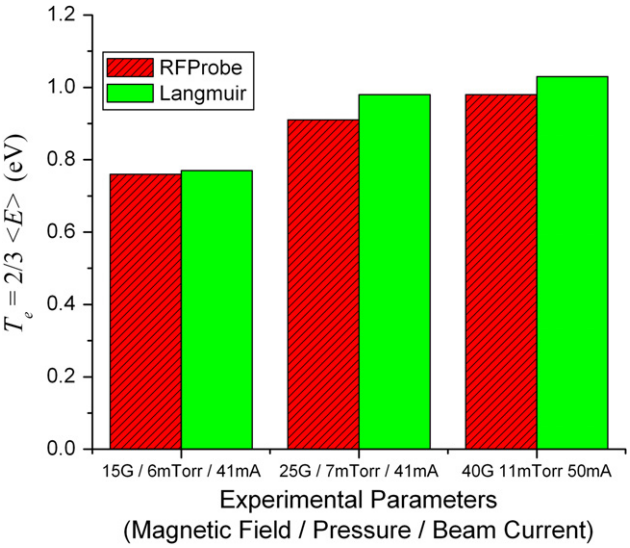

Figure 3. A comparison effective T_e measurements by the Langmuir probe and RF probe for a variety of plasma conditions.

3.1. Results for f(E) and T_e

Measurements of $f(E)$ from the RF probe and the Langmuir probe yielded good agreement in both shape and average energy, as illustrated in figure 2. For consistency the data acquisition routines used with the Langmuir probe and the RF probe employed 0.1 V steps between voltage points, and in both cases similar time-averaging routines were employed to minimize noise in the raw data. Figure 2 shows that the $f(E)$ values obtained with the two probes agree well at high energies but with some variation near the peak of the distribution functions.

To quantify the agreement between $f(E)$ measured by the RF probe and Langmuir probe, an effective T_e was calculated from the EEDFs of the respective probes as follows:

$$T_e = \frac{2}{3}\langle E\rangle = \left(\frac{2}{3}\right)\frac{\int_0^\infty E \cdot f(E)\,\mathrm{d}E}{\int_0^\infty f(E)\,\mathrm{d}E}. \quad (9)$$

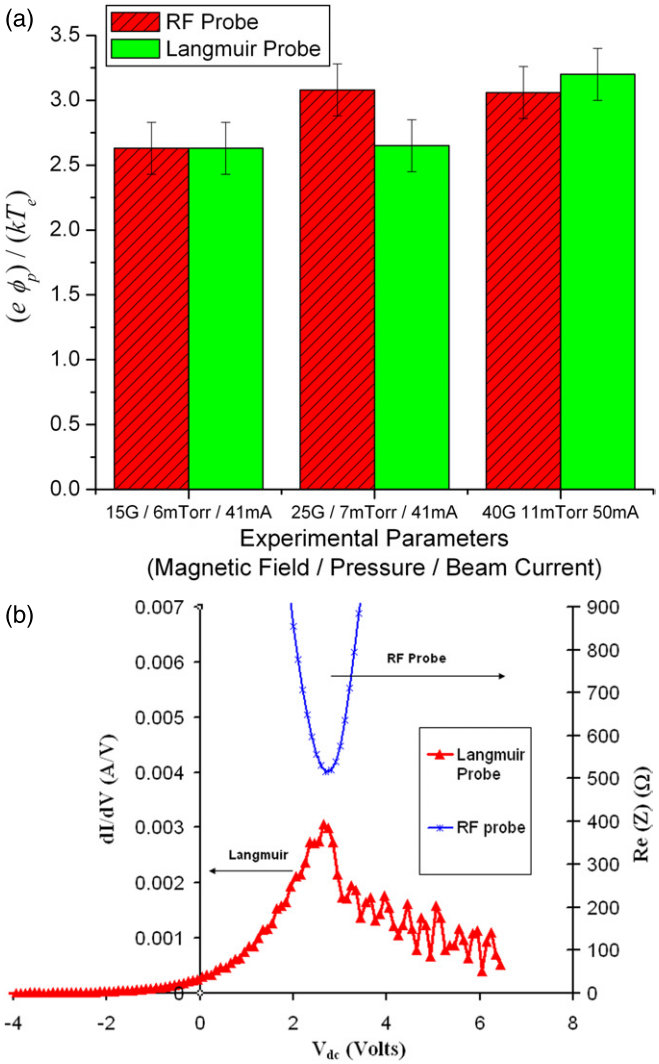

Figure 4. (*a*) Plasma potential measurements scaled by the measured the electron temperature for three different experimental parameters. (*b*) The data set specific to the 25 G/7 mTorr/41 mA case. In all cases the error bars were determined by the full width at 90% of the maximum for the Langmuir probe measurements and full width at 10% above minimum for RF probe data.

Applying this procedure to the $f(E)$ measurements in figure 2 yields $T_e = 0.98$ eV and $T_e = 1.03$ eV for the RF probe and Langmuir probe, respectively. Once again, this behavior was reproducible over the range plasma conditions tested and is reflected in figure 3, which plots T_e calculated from the EEDFs for a range of plasma densities from 9×10^9 to 7×10^{10} cm^{-3}. Generally the T_e measurements from the two probes agreed to within a few per cent.

3.2. *Results for φ_p and n_e*

The determination of φ_p and n_e showed good agreement for the two probes across an order of magnitude variation in plasma density, as illustrated in figures 4 and 5. Over most of this range the two probes agreed to within the experimental error. The two specific data sets shown in figure 4(*b*) demonstrate the good agreement between the minimum in Re(Z_{ac}) for the RF probe and the peak in the first derivative of the Langmuir probe trace.

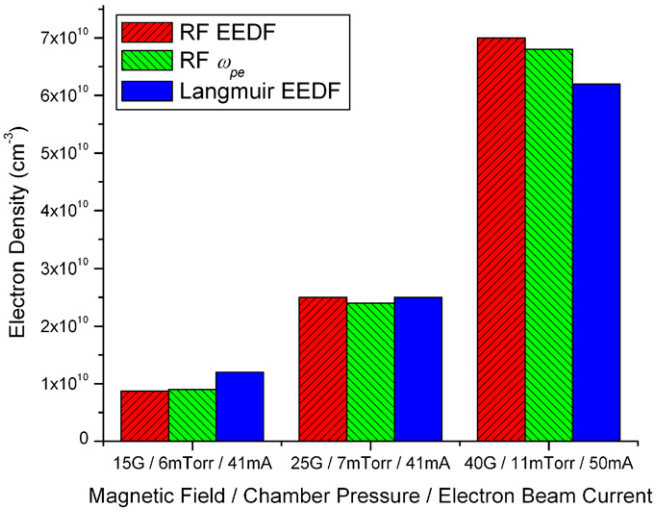
RF EEDF
RF ω_{pe}
Langmuir EEDF
Electron Density (cm^{-3})
15G / 6mTorr / 41mA
25G / 7mTorr / 41mA
40G / 11mTorr / 50mA
Magnetic Field / Chamber Pressure / Electron Beam Current

Figure 5. Electron density measurements for a variety of experimental parameter settings obtained using the integration of $f(E)$ from both the RF probe and Langmuir probe, and also n_e obtained from ω_{pe}.

The densities calculated from the RF probe and Langmuir probe data are shown in figure 5. The density was calculated by integrating the respective EEDFs obtained with the RF probe and Langmuir probe using equation (8). Like $f(E)$ and T_e, the two density calculations showed good agreement for the two probes. As a check, RF data were also taken at high frequency to determine the electron plasma frequency ω_{pe}, from which a density value was calculated. The value from ω_{pe} again agreed well with the results obtained by integrating $f(E)$.

4. Summary and conclusion

The results presented here show that RF probes are a good alternative to Langmuir probes for measuring plasma parameters. In particular, at typical processing plasma densities in argon, the values from the two probes agreed to within 15% or better. For measurements of φ_p and T_e the measurements agreed to within experimental error. This agreement provides strong support for the theoretical basis on which biased RF probe measurements are based [13].

However, while RF probes are highly capable plasma diagnostics, they are not a cure-all. In particular, the variable bias RF probe techniques for measuring φ_p and $f(E)$ are susceptible to the same contamination issues that plague Langmuir probes when used in reactive gases or depositing plasmas. Nevertheless, whereas such environments can render Langmuir probes completely ineffective, RF probes are still able to measure the plasma density n_e by employing high frequencies.

The measurements of $f(E)$ in this work highlight some potential advantages of RF probes over Langmuir probes, in that the former effectively measure the first derivative of the dc current–voltage trace, thus reducing noise amplification from differentiation when obtaining φ_p and $f(E)$. Also, the broad

band of frequencies provided by the network analyzer allows ion effects to be largely eliminated, a feature that is especially useful when determining the tail of $f(E)$.

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